# SPACE PROCESSING OF CRYSTALLINE MATERIALS: A STUDY OF KNOWN METHODS OF ELECTRICAL CHARACTERIZATION OF SEMICONDUCTORS



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J. G. Castle



APPENDIX
to
Final Technical Report
(Bibliography)

This study was supported by the

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# APPENDIX

## BIBLIOGRAPHY

The enormous volume of semiconductor publications were searched in late '74 for descriptions of experimental techniques for the electrical characterization of semiconductors, aiming especially for those techniques most likely to be suitable for NASA's space processing program. No descriptions of noncontacting techniques with adequate resolution and precision were found in the regular journals, but the trade journals for electronics and optics revealed in 1974 and 1975 several specific references to successful measurements of electrical and/or optical uniformity with the appropriate high precision (circa 1%) and appropriate high resolution (circa microns). The selected bibliography on electrical characterization techniques for semiconductors is given below, arranged alphabetically by first author. The older publications are included for historical interest or theoretical background.

The emphasis for inclusion in this bibliography was on:

1. representative semiconductors -
   mostly Si for the elemental semiconductors,
   mostly GaAs for the III-V compounds, and
   mostly CdS for the II-VI compounds.
2. non-contacting techniques for the standard electrical parameters to suit NASA's need for monitoring crystal growth in space, preferably in real time with high resolution.

It should be noted here (as in the text) that the largest impact of NASA's space processing of semiconductors may well be in those significant applications of special characteristics, such as the negative differential

permittivity for hot electrons in GaAs and the lunimescence from SiC which are not well covered in this search.

The attached list includes labels from the categories in Table I of the text. They are summarized in the following Table.

| Freq Used<br>El Parameter | DC to RF | MW | IR & OP |
|---|---|---|---|
| RHO | Bulk Resistance | | |
| | Coil Loading<br>(Skin Effect) | Surface Resistance<br>(Skin Effect) | |
| MU | Hall Effect | MW Hall Effect<br>Faraday Rotation | Faraday Rotation |
| DMU | Gunn Effect | High Field<br>Permittivity | Differential<br>Photovoltage |
| TAU<br>and/or<br>IMP<br>or<br>DEF(ects) | | Electron Spin Resonance<br>(ESR)<br>Cyclotron Resonance<br>Photoinduced MW RHO | Photovoltage<br>(PV)<br>Photoinduced DC RHO<br>Photoluminescence<br>(PL)<br>Absorption Spectrum |

So, for example, an article by G. Feher in 1960 on electron spin resonance (ESR) in silicon would be alphabetized as FEHE60 and labelled with the category TAU-MW or IMP-MW depending on the author's emphasis. Similarly, the second article by L. W. Patrick and W. J. Choyke in 1965 on SiC photoluminescence (PL) would be listed under PATK65 and labelled IMP-OP.

Review articles and books are labelled as a separate group, called REVIEW.

ABST73 "Extended Abstracts of Dielectrics and Insulation Division." REVIEW (OP)

The Electrochemical Society, Inc., Spring Meeting, Chicago, Ill., Vol. 73#1, (May 13-18, 1973).

- Includes a variety of techniques for scanning semiconductor surfaces for electrical characteristics.

APS75 "Report to the American Physical Society by The Study Group on Radiation Effects on Materials, Section X, Semiconductors." REVIEW

(Si) F. L. Vook, chairman, and APS Study Group Participants. Rev. Mod. Phys., Sec. X, Vol. 47, Suppl 3 (Winter 1975).

- Summary of the rather extensive information from ESR on point defects in silicon, citing the paucity of defect inventories in other semiconductors and the need for further electrical characterization of defect processes.

BULL68 "Measurement of Carrier Lifetime in Semiconductors - An Annotated Bibliography Covering the Period 1949-1967." REVIEW

W. Murray Bullis, National Bureau of Standards, Wash., DC, NBS TN 465; AFML TR 68 108 70P (1968).
Microfiche: AD 674 627

BULL68B "Methods of Measurement for Semiconductor Materials, Process Co--etc." REVIEW

W. M. Bullis, National Bureau of Standards, Wash., DC, (Dec 1968).
Microfiche: AD 681 330.

BULL69 "Methods of Measurement for Semiconductor Materials, Process Co--etc." REVIEW

W. M. Bullis, National Bureau of Standards, Wash., DC, (Feb 1969).
Microfiche: AD 683 808

BULL69 "Methods of Measurement for Semiconductor Materials, Process Control and Devices." REVIEW

W. M. Bullis, National Bureau of Standards, Wash., DC, NASA-CR-106280, Quarterly Report, 1 April - 30 June 1969, pp. 46 (Nov 1969).
Microfiche: N69-39759

BULL69B "Methods of Measurement for Semiconductor Materials, Process Control and Devices." REVIEW

W. M. Bullis, National Bureau of Standards, Wash., DC, Quarterly Report, 1 January - 31 March 1969, NASA-CR-101692 (Aug 1969).
Microfiche: N69-30167

BULL70 "Methods of Measurement for Semiconductor Materials, Process Control and Devices." REVIEW

W. M. Bullis, National Bureau of Standards, Wash., DC, Quarterly Report 1 October - 31 December 1969, NASA-CR-110211, pp. 64 (August 1970).
Microfiche: N70-28987

BULL70 "Methods of Measurement for Semiconductor Materials, Process Control and Devices." REVIEW

W. M. Bullis, National Bureau of Standards, Wash., DC, Quarterly Report for 1 July - 30 September 1969, NBS-TN-520, pp. 71 (March 1970).
Microfiche: N70-24156

BULL71 "Methods of Measurement for Semiconductor Materials, Process Control and Devices." REVIEW

W. M. Bullis, National Bureau of Standards, Wash., DC, Quarterly Report, 1 July - 30 September 1970, pp. 60 (April 1971).
Microfiche: N71-24975

BULL71B "Methods of Measurement for Semiconductor Materials, Process Control and Devices." REVIEW

W. M. Bullis, National Bureau of Standards, Wash., DC, NASA-CR-123167, pp. 54 (October 1971)
Microfiche: N71-38504

GRIF71 "Microwave Methods of Studying Semiconductor Materials." REVIEW

E. W. Griffin; RADC-TR-71-Z8(U); February 1971; Cornell University, Ithaca, NY, School of Elec Engr.
Microfiche: AD716869 (3 cards).

HARV65 "Microwave Engineering." REVIEW

A. F. Harvey, McGraw-Hill Book Co., NYC, (1965).

- Basic theory of wave propagation in circuits, especially mode charts. Basic design considerations for resonant cavities and filter circuits, including shim effect and extensive references.

KANE70 Book - "Characterization of Semiconductor Materials." REVIEW

Philip F. Kane and Graydon B. Larrabee; McGraw-Hill Book Co., ISBN: 07-033273-8 (1970)

KULI70 "Physical Characterization of Electronic Materials, Devices and Thin Films." REVIEW

(GaSe) S. A. Kulin , E. V. Clougherty, AFCRL-70-0050; January 1970, Manhabs, Inc., Cambridge, Mass.
Microfiche: AD 703275 (1 Card)

- High pressure synthesis of Group IV analog compounds.

MARS70 "Silicon Device Processing." REVIEW

(Si) C. P. Marsden (National Bureau of Standards), NBS-SP-337; November 1970, pp. 469
Microfiche: N71-17276 (8 cards).

MATA71 Book - "Defect Electronics in Semiconductors" REVIEW

H. F. Matare, John Wiley & Sons, Inc., ISBN: 0-471-57618-2, LCCC: 79-138916 (1971).

- Defects that affect electrical properties of semiconductors are reviewed, especially with respect to their influence and applications in devices. Measurement techniques are summarized in a seventy page appendix.

MILN73 Book - "Deep Impurities in Semiconductors." REVIEW

A. G. Milnes, John Wiley & Sons, Inc., ISBN 0-471-60670-7 (1973)

- This book reviews the deep traps formed by a variety of specific impurities in Si and Ge, in GaAs and other III-V compounds. Photoconductivity involving two wavelengths of light and also high field permittivity are discussed, as are techniques for lifetime measurements.

SZE68 "Resistivity, Mobility and Impurity Levels in GaAs, Ge and Si at 300°K." REVIEW

(Ge, Si, GaAs) S. M. Sze and J. C. Irvin, Solid-State Electronics, Pergamon Press Vol. 11, 599 (1968).

- The resistivity and mobility data of GaAs at 300°K have been analyzed by least-square method and plotted as a function of the impurity concentration. The measured impurity levels in GaAs have been presented in graphical form for the most accurate and up-to-date values. For convenient reference the published results for Ge and Si are also presented.

CHAT70 "Transient Method of Measuring Very Low Conductivities Without Contacting Electrodes." DC-RHO RF-RHO

Daniel Chatain, Pierre Gautier and Colette Lacabanne, Rev. Sci. Instrum., Vol. 41#11, 1610 (November 1970).

- An experimental procedure is proposed, which amounts to Fourier transforming the frequency depending torque in the Ogawa's torsion pendulum method. This reduces by a factor of the order 100 the fairly long times needed for measuring the very low conductivities of insulating materials.

COWL62 "Apparatus for the Rapid Scanning of the Seebeck Coefficient of Semiconductors." DC-IMP

L. E. J. Cowles and L. A. Dauncey, J. Sci. Instrum., Vol. 39, pp. 16 (1962).

MUIR71 "Simple Apparatus for Measuring Thermoelectric Power of Small Samples from 80 to 650K." DC-IMP

James A. Muir, Rev. Sci. Inst., Vol. 42 (Jan-June 1971).

VORO70 "Use of a Thermoelectric Probe in an Investigation of the Diffused Impurity Distribution in Layers." DC-IMP

(GaAs:Zu) T. I. Voronina, Yu. A. Gol'dberg, O. V. Emel'yanenko and R. P. Kesamanly, translated from Fizika i Tekhnika Poluprovodnikov, pp. 1591-1593, October 1969; Soviet Physics-Semiconductors, Vol. 3#10, 1338 (April 1970).

- This paper reports the results of an investigation of the diffusion profile of zinc in gallium arsenide, which was deduced by measuring the thermoelectric power during successive removal of layers.

WOLF70 "Ionized Impurity Density in n-Type GaAs." DC-IMP

(GaAs) C. M. Wolfe, G. E. Stillman and J. O. Dimmock, Journal of Applied Physics, Vol. 41#2, 504 (Feb 1970).

- Total ionized impurity densities ($N_D+N_A$) from $7x10^{13}$ to $3x10^{17}cm^{-3}$ are determined for epitaxial samples of n-type GaAs by analyzing mobility and carrier concentration data as a function of temperature with the Brooks-Herring formula for ionized impurity scattering. This procedure results in the determination of a temperature range within which the effects of other scattering mechanisms are minimal and gives values of $N_D$ and $N_A$ which are in good agreement with impurity densities obtained from analyses of the temperature variation of the Hall constant. These results are then used to determine empirical curves relating the impurity density to the 77°K Hall mobility. With these data a good estimate of the total ionized impurity concentration in a sample can be determined from Hall constant and resistivity measurements at 77°K.

RUFF68 "Determination of Resistivity and Hall Coefficient of Semiconducting Materials Between 80°K and 375°K." DC-MU

R. C. Ruff, NASA-TM-X-53763, pp. 43 (6 August 1968). Microfiche: N68-33020.

MCKI69 "Systematic Errors in Alternating Current Hall Effect Measurements." AC-MU

H. L. McKinzie and D. S. Tannhauser, Journal of Applied Physics, Vol. 40#12, 4954 (November 1969).

BRIC61 "Contactless Resistivity Meter for Semiconductors." RF-RHO

(GeSiGaAs) J. C. Brice and P. Moore, Mullard Research Laboratories, Salfords, Surrey, Journal of Scientifc Instruments, Vol 38, 307 (July 1961).

- This note describes a simple apparatus for the comparative determination of resistivity in the range $10^{-3}$ to 10 ohm cm, using the eddy-current principle. Eddy currents are induced in the specimen by a flat spiral inductor forming part of the tuned circuit of an oscillator working at about 10 Mc/s.

BROW64 "A Non-Contact Resistivity Meter." RF-RHO

A. C. Brown, J. Sci. Instrum., Vol. 41, (1964).

- An instrument is described which can measure the resistivity of slices of semiconducting material. It is suitable for resistivities of the order of milliohm cm. The calibration of the instrument is calculable from theory. Resistivity is indicated by a frequency to which it is linearly related.

CHAB71 "Contactless Induction Method for Electric Resistivity Measurement." RF-RHO

Aleksander Z. Chaberski, J. Appl. Phys., Vol. 42#3, 940 (1 March 1971).

- A new absolute method is developed for measuring electric resistivity in the range of $10^{-8}$ to $10^{+8}$ ohm-cm of a sample of almost arbitrary shape. This method takes into account the effect of self-induced conduction and polarization current. Measurements are made with the specimen placed in a constant rotating magnetic field in such an orientation that it experiences maximum torque and has minimum moment of inertia.

FISC69 "Direct Determination of Skin Depth by a Radio-Frequency Size Effect." RF-RHO

(Bi) Harris Fischer and Yi-Han Kao, Solid State Communications, Pergamon Press, Vol. 7, pp. 275-277 (1969).

- A size-dependent absorption peak is observed when single- or poly-crystal Bismuth slabs at liquid Helium temperatures are situated in the tank coil of a marginal radio-frequency oscillator and subjected to a magnetic field H.

HAIS67 "Electrodeless Measurement of Resistivities Over a Very Wide Range." RF-RHO

R. W. Haisty, Rev. of Sci. Instrum., Vol. 38#2, 262 (Feb 1967).

- Resistivity of electronic conductors, from metals to semi-insulators, is determined from the change in grid current of a high frequency oscillator owing to the loading resulting from eddy currents in the sample. A typical calibration curve, made at 14 Mc and covering the range $10^{-4}$ Ω-cm to $10^{8}$ Ω-cm is given; application to the estimation of sample homogeneity is discussed.

HAIS68 "Measurements of High Resistivities by the Electrodeless Falling Sample Method." RF-RHO

R. W. Haisty, Rev. Sci. Inst., Vol. 39#5, pp. 778 (1968).

HAMD73 "Measurement of Resistivity Change by a Mutual Inductance Method." RF-RHO

A. J. Hamdani, J. Appl. Phys., Vol. 44#8, 3486 (August 1973).

- The resistivity of a nonferromagnetic conductor can be deduced from the change in mutual inductance between two coils when the sample is inserted. A method is described for measuring mutual inductance over a range of frequencies and this can be used to detect change in resistivities of the order of $+10^{-13}$ ohm-cm.

MIYA67 "Contactless Measurement of Resistivity of Slices of Semi-Conductor Materials." RF-RHO

Nobuo Miyamoto and Jun-Ichi Nishizawa, The Rev. of Sci. Instrum., Vol. 38#3, 360 (March 1967).

- In this resistivity measurement, a pair of semicircular measuring electrodes is connected to a series or parallel resonance circuit composed of an inductance L and a variable capacitance C. A sample is coupled capacitively with the electrode with no direct contact. The authors' method is similar to the Q meter method in principle, but uses a comparative measurement.

OGAW61 "Measurement of the Electrical Conductivity and Dielectric Constant Without Contacting Electrodes." RF-RHO OP-RHO

(CdS) Tomoya Ogawa, J. Appl. Phys., Vol. 32#4, 583 (April 1961).

- A method is developed whereby electrical conductivity and dielectric constant of semiconducting and dielectric materials without contacting electrodes can be measured. The principle of this method is that a specimen suspended in a rotating field with a fine fiber is rotated by the torque proportional to the electrical conductivity or the imaginary part of its complex dielectric constant, and the torque exerted on it by a linearly polarized field is proportional to the real part of its dielectric constant.

VERN72 "Measurements of the Resistivity of Semiconductors by Means of Eddy Currents." RF-RHO

(Si) Yu. M. Vernigorov and A. M. Fedulov, translated from Pribory i Tekhnika Eksperimenta, No. 1, pp. 203-204, Jan-Feb 1972; Inst. and Exp. Tech. Vol. 15#1, 235 (1972).

- A method is proposed for determining the resistivity of semiconductor disks by means of eddy currents. From the solution of the problem of the influence of a conducting disk on a turn carrying a current which varies according to a harmonic law, the relationship is obtained between the magnitude of the resistance reflected into the turn and the electrophysical and geometric parameters of the semiconductor disk. The calculation error was estimated experimentally and does not exceed 10% in comparison with the results of contact measurements performed on single-crystal semiconductor disks.

NYBE62 "Electrodeless Techniques for Semiconductor Measurements." RF-MU

D. W. Nyberg and R. E. Burgess, Canadian Journal of Physics, Vol. 40, 1174 (1962).

- Electrodeless methods, based on the inductive coupling of samples to coils, for determining the electrical conductivity, the Hall mobility, and the magneto-resistance of a semiconductor are described. The theory is developed for cylindrical and spherical geometry samples and design considerations and experimental techniques are discussed.

YANK70 "Hall Effect for Eddy Currents in a Semiconductor." RF-MU

(InSb) Z. K. Yankauskas, translated from Fizika Tverdogo Tela, pp. 2642-2644, September 1969; Soviet Physics-Solid State, Vol. 11#9, 2131 (March 1970).

BETH43 "Lumped Constants for Small Irises." MW-RHO

H. A. Bethe, MIT Radiation Laboratory, Report 43-22 (March 24, 1943).

- The basic calculation of the constants which describe the microwave coupling through an iris.

CAST75 "Electrical Characterization of GaAs Single Crystal in Direct Support of M555 Flight Experiment." MW-RHO OP-IMP

(GeSe) (GaAs) J. G. Castle, NASA CR-143986, Final Technical Report under Contract No. NAS8-29542 (October 1975).

- Two methods of obtaining the microwave skin depth, one for mapping flat surfaces and the other for analyzing the whole surface of small single crystal wafers, were developed to the stage of working laboratory procedures. The preliminary 35 GHz data characterizing the two types of space-related single crystal surfaces, flat slices of gallium arsenide and small wafers of germanium selenide, are discussed. A third method of nondestructive mapping of donor impurity density in semiconductor surfaces by scanning with a light beam was developed for GaAs.

CHAM67 "Electrodeless Determination of Semiconductor Conductivity from $TE_{01}{}^{o}$-Mode Reflectivity." MW-RHO

K. Champlin, J. D. Holm and G. H. Glover, Journal of Applied Physics, Vol. 1, 96 (January 1967).

- A technique utilizing the $TE_{01}{}^{o}$-mode of circular waveguide in a "reflection coefficient bridge."

DONO56 "High Frequency Conductivity in Semiconductors." MW-RHO

B. Donovan and N. H. March, Departments of Physics, Bedford College, London and University of Sheffield, p. 528 (1956).

- Historical calculation of the electrical conductivity in alternating fields is developed for non-degenerate semiconductors with spherical energy surfaces.

IREM69 "Noncontact Method of Measuring Temperature Dependence of Electrical Conductivity of Semiconducting Materials." MW-RHO

D. V. Iremashvili, N. I. Leont'ev, G. M. Mailov and A. I. Shimko, Instrum. and Exp. Tech, Vol. 12#2, 1022 (July-Dec 1969).

- A noncontact method of measuring specific resistance of semiconducting samples in a wide range of temperatures (20-800°C) with the use of a super high frequency cavity resonator is described.

JACO67 "New Microwave Techniques in the Measurement of Semiconductor Phenomena." MW-RHO

H. Jacobs, F. A. Brand, J. D. Meindl, S. Weitz, U. S. Army Signal Research and Development Laboratory, Fort Monmouth, N.J. and R. Benjamin, Monmouth College, West Long Branch, N.J. I.R.E. International Convention Record, p. 30 (1962)

- Techniques have been developed using microwave transmission and reflection to determine the physical constants of crystals such as the bulk lifetime, surface recombination velocity, resistivity and dielectric constant. One of the most recent developments involving the profiling of ingot resistivity and lifetime by a microwave reflection method promises to be as accurate and less complicated than the more conventional dc conductivity techniques.

LIND63 "Reflection of Microwaves from Semiconductors." MW-RHO

J. Lindmayer and M. Kutsko, Solid State Electronics, Pergamon Press, Vol. 6, pp. 377-381 (1963).

- Reflection of microwave energy from a semiconductor is calculated and measured. The wave guide is terminated by a semiconductor-metal sandwich.

LINH56 "A Microwave Resonant Cavity Method for Measuring the Resistivity of Semi-Conducting Materials." MW-RHO

J. G. Linhart, M. Templeton and R. Dunsmuir, Research Laboratories, British Thomson-Houston Co., Ltd., Rugby, British Journal of Applied Physics, Vol. 7, 36 (January 1956).

- Historical description for measuring the resistivity of semiconductors at centimetre wavelengths.

SAND62 "Comments on Electrodeless Measurements of Semiconductor Resistivity at Microwave Frequencies." MW-RHO

O. Sandus, Proceedings of IRE. Vol. 50, Corres., 473 (1962).

GERS70 "Determination of the Carrier Mobility and Density in Semiconductors Using a Bimodal Microwave Resonator." MW-MU (MW-IMP)

E. M. Gershenzon and V. N. Martsinkevich, Soviet Physics - Semiconductors, Vol. 4#3, 450 (September 1970).

- An analysis is given of the possibility of measuring the mobility and density of free carriers in semiconductors in the microwave range, using a bimodal resonator in a wide range of temperatures and magnetic fields. The results of the calculations are compared with experimental data on n-type Ge.

GERS71A "Use of a Bimodal Resonator in the Determination of the Mobility of Carriers of the Same Sign but with Different Effective Masses." MW-MU

E. M. Gershenzon and V. N. Martsinkevich. Soviet Physics - Semiconductors, Vol. 4#9, 1557, (March 1971).

- A bimodal resonator could be used to measure the parameters of semiconductors with two types of carrier of the same sign but with different effective masses, such as the mobilities of the light and heavy holes in Ge.

GERS71B "Potentialities of a Bimodal Resonator in the Measurement of $\mu$ of High-Mobility Semiconductors." MW-MU

E. M. Gershenzon and V. N. Martsinkevich, Soviet Physics - Semiconductors, Vol. 4#9, 1559 (March 1971).

- A bimodal resonator with two degenerate $TE_{11n}$ modes can be used successfully to measure the parameters of semiconductors at microwave frequencies in a wide range of temperatures and magnetic fields.

NISH58 "Measurement of the Hall Mobility in η-Type Germanium at 9121 Megacycles." MW-MU

(Ge) Y. Nishina and W. J. Spry, J. Chem. Phys. - Letter (Early 1958).

- The Hall mobility of free carriers in a single crystal of 16 ohm-cm η-type germanium was measured at 9121 Mc in a dual mode resonant cavity at room temperature. A microwave value of 2900 $cm^2$/volt sec was obtained in comparison to a measured dc value of 2670 $cm^2$/volt sec. The dc measurement was made on a second sample cut from the same germanium crystal.

PORT58 "Microwave Faraday Rotation: Design and Analysis of a Bimodal Cavity MW-MU MW-IMP

A. M. Portis and Dale Teaney, Journal of Applied Physics, Vol. 29#12, 1692 (December 1958).

- The design and analysis of a bimodal cavity for the observation of microwave Faraday rotation is presented.

SRIS71 "Microwave Transmission Through P-Type Germanium." MW-MU

G. P. Srivastava and A. K. Jain, J. Phys. C:Solid St Phys., Vol. 4, 364 (1971).

- Microwave power transmission for both the circular modes and the linear mode of polarization through p-type germanium has been used to estimate the mobilities due to impurity scattering and thermal scattering.

ACKE67 "Determination of the Negative Differential Mobility of η-Type Gallium Arsenide Using 8mm Microwaves." MW-DMU

(GaAs) G. A. Acket, Physics Letters, Vol. 24A#4, 200 (13 Feb 1967).

- Experimental data concerning the negative slope-mobility in η-GaAs are presented. It is generally accepted that the Gunn-instability [1] in η-GaAs is due to a differential negative conductance arising from electron transfer from the high-mobility (000) conduction band minimum towards the low-mobility (100) satellite minima. In this note we should like to report on measurements of the current-voltage characteristic of η-GaAs by high-power microwaves, using a modification of the technique used by Zucker et. al. [8] for germanium and silicon. This method was chosen since at sufficiently high frequency no build-up of instabilities will be possible because the material is swept very rapidly into and out of the negative-mobility range.

GLOV71 "Error in Microwave Measurements of the Velocity-Field Characteristics of η-Type GaAs Due to Energy Relaxation Effects." MW-DMU

(GaAs) G. H. Glover, Applied Physics Letters, Vol. 18#7, 290 (April 1, 1971).

- It is shown theoretically that the average drift velocity of electrons in GaAs as measured by microwave techniques differs substantially from the dc characteristic. This error, arising from electron-energy relaxation effects, has always been neglected in past measurements. The simple model predicts an error of 16% in measured velocity at 35 GHz.

GLOV71 "High-Field Microwave Permittivity of Electrons in Bulk GaAs." MW-DMU

(GaAs) G. H. Glover, Journal of Applied Physics, Vol. 42#13, 5590 (December 1971).

- Measurements of the permittivity of bulk η-type GaAs have been obtained at a frequency of 35 GHz with microwave heating field strengths up to 16 kV/cm. The measurements are in good agreement with predictions of a simple two-valley model using an energy-independent thermal relaxation time $\tau_T = 1.5 \times 10^{-12}$ sec. The peak value of the large-signal permittivity is found to be considerably smaller than the small-signal high-field values reported in the past. This disparity is substantiated by calculations with the two-valley model. It is felt that the large-signal function measured here is considerably more relevant to LSA-mode circuit design, as well as to calculations of electron parametric operation, than small-signal values.

INOU71 "Microwave Measurement of the Velocity-Field Characteristics in η-Type Gallium Arsenide." MW-DMU

(GaAs) Masataka Inoue, Junji Shirafuji and Yoshio Inuishi, Japanese Journal of Applied Physics, Vol. 10#10, 1378 (October 1971).

- In order to clarify the reasons of large conflict in the velocity-field characteristics of GaAs among many experiments reported so far the effects of nonuniform conductivity and low field mobility on the velocity-field characteristics are investigated using a microwave-heating technique. Various degrees of nonuniformity are introduced by serial irradiation of electrons on a localized portion of the sample. The results show that the threshold field, peak velocity and negative differential mobility increased with increasing the nonuniformity.

KANE71 "Microwave Anisotropy and Frequency Dependence of Hot Electron in η-Type GaAs." MW-DMU

(GaAs) Shigeo Kaneda and Masayuki Abe, Japanese Journal of Applied Physics, Vol. 10#10, 1396 (October 1971).

- The physical mechanism of the microwave anisotropy due to the hot electron effect in a semiconductor bulk is at first investigated phenomenologically for the case that a relative spatial angle θ between a small microwave electric field and a high intensity electric bias field is arbitrary. And then, the microwave anistropy and the frequency dependence in η-type GaAs are analyzed by using the Boltzmann transport equations. Conclusively, the microwave anisotropy is especially remarkable in the region of negative resistance.

BLAG70 "Determination of the Impurity Concentration in Germanium from Cyclotron Resonance." MW-IMP

(Ge) L. E. Blagosklonskaya, E. M. Gershenzon and Yu. P. Ladyzhinskii. V. I. Lenin Moscow State Pedagogical Institute translated from Fizika i Tekhnika Poluprovodnikov, Vol. 4, No. 6, pp 1187-1189, June 1970. Original article submitted January 9, 1970.

- Cyclotron resonance is widely used in investigations of the mechanism by which the momentum of free carriers in semiconductors is dissipated. The present paper is concerned with the possibility of using cyclotron resonance to determine the concentration of impurities in germanium by measuring the contribution of the scattering by neutral impurities to the cyclotron line width. Such determinations of the impurity concentration have been made already (1, 2). A detailed investigation of the scattering by neutral impurities, reported in (3, 4), is the basis of the method suggested here.

CAST63 "Raman Spin-Lattice Relaxation of Shallow Donors in Silicon." MW-IMP

(Si) Theodore G. Castner, Jr., Physical Review, Vol. 130#1, 58 (1 April 1963).

This work reports both experimental measurements and calculations of two-phonon Raman spin-lattice relaxation times for shallow donors in silicon, Saturation, line broadening and adiabatic fast passage techniques were used to measure $T_S$ ($\Delta M_S=\pm 1, \Delta M_I=0$) between 2 and 30°K for P, As, Sb and Bi at 3300 G.

WAGN73 "Spin-Lattice Relaxation of $Mn^{2+}$ in Hexagonal CdS below 4.2°K MW-IMP

(CdS) G. R. Wagner, J. Murphy and J. G. Castle, Jr., Physical Review B, Vol. 8#7, 3103 (1 October 1973).

- The spin-lattice relaxation of $Mn^{2+}$ in hexagonal CdS has been studied at X band in the temperature range 1.3-4.2°K using inversion-recovery techniques.

DONO55 "The Hall Effect in Metals at High Frequencies." IR-TAU

B. Donovan, Department of Physics Northern Polytechnic, London. Proc. Phys. Soc. Vol. , 1026 (1955)

- Historical calculations of the Hall coefficient have been carried through for a metal with two overlapping energy bands, and the variations with frequency and with field strength are shown graphically for certain special cases.

DONO54 "The Magneto-Resistance Effect in Metals at High Frequencies." IR-RHO

B. Donovan, Department of Physics, Northern Polytechnic, London. Proc. Phys. Soc. Vol. LXVII#4-A, p. 22 (1954).

- Historical description of effect of interband scattering on MW and IR surface resistance.

CHAN73 "Quantitative Piezospectroscopy of the Ground and Excited States of Acceptors in Silicon." IR-IMP

(Si) H. R. Chandrasekhar, P. Fisher, A. Romados and S. Rodriguez. Phys. Rev. B8 3836 (1973).
- PA and PL vs. external stress.

FOSS73A "Radiative Recombination of Electron-Hole Pairs Generated by Two-Photon Absorption in Indium Autimonide." IR-IMP

(InSb) H. J. Fossum, B. Aucker-Johnson. Phys. Rev. B8 2850 (1973).

- Photoluminescence.

FOSS73B "Excess Carriers Induced in Indium Antimonide with a Carbon-Dioxide Laser." IR-IMP

(InSb) H. J. Fossum, W. S. Chen and B. Ancker-Johnson. Phys. Rev. B8, 2857 (1973).

- Photoinduced conductivity.

KEEN71 "Pseudo-Brewster Angle Determination of Carrier Concentration." IR-IMP

(Si) W. A. Keenan and P. A. Schumann, Jr., J. Electrochem. Soc.: Solid State Science, Vol. 118, 2010 (December 1971).

- An infrared, optical constant model for semiconductors has been used to calculate calibration curves relating carrier concentration in silicon to the pseudo-Brewster angle for several wavelengths, the range of carrier concentrations being limited by the wavelength employed. Experimental results for silicon are presented for a wavelength of 3.391 μm.

KEEN72 "Pseudo-Brewster Angle Concentration Determination: Apparatus Reproducibility and Accuracy." IR-IMP

(Si) W. A. Keenan, C. J. Liu and C. P. Schneider, J. Electrochem. Soc., Vol. 119, 522 (1972).

- The angle of incidence at which the parallel component of polarized infrared reflected light attains a minimum (the pseudo-Brewster angle, or PBA) is used to determine semiconductor carrier concentrations. A PBA apparatus using a 3.391 He-Ne laser as a polarized light source is described. Experimental results for n- and p-type silicon are compared with plasma resonance and sheet resistance measurements to determine best fit of theoretical calibration curves. Results of reproducibility and correlation studies are also presented.

KESS72 "Optical Constants and Free Carrier Data of Heavily Doped Semiconductors from Reflection Measurements in the Infrared." IR-TAU

(Si) F. R. Kessler and E. Barta, Phys. Stat. Sol. (a), Vol. 9, 469 (1972).

- A method for determining the optical constants of heavily doped semiconductors in the infrared and free carrier parameters is described, which requires one reflectivity measurement only. The method is based upon an analysis of the reflectivity spectrum in the region of the plasma resonance frequency. The analysis takes account of the energy dependence of the relaxation time. This method allows an accurate determination of the index of absorption even for $k<0.2$ in spite of the simple experimental setup. $m^*$ and $\tau$ data and optical constants so determined are presented for n- and p-type silicon.

LAMB72 "Free-Carrier Reflectivity in Optically Inhomogeneous Silicon." IR-IMP

(Si) L. M. Lambert, J. Appl. Phys., Vol. 43#11, 4612 (Nov 1972).

- Interpretation of reflectivity data from the surface of a semiconductor containing an impurity gradient and, in particular, a p-n junction is of practical importance. Current theories predict a shift in the wavelength of the reflection minimum to shorter wavelengths. In this theory and subsequent measurements, such behavior was not observed; in fact, almost no shift of wavelength occurred even for the most lightly doped and shallow junction samples. The results obtained indicate that the surface free-carrier concentration can be obtained directly from a reflectivity measurement.

MATT72 "Carrier Lifetime Measurements by the Photoconductive Decay Method." IR-IMP

R. L. Mattis, National Bureau of Standards, Wash., DC, NBS-TN-736 (Sept 1972).
Microfiche: N73-22685

MURR66 "Infrared Reflectivity of Heavily Doped Low-Mobility Semiconductors. I. GaAs." IR-IMP

(GaAs) L. A. Murray, J. J. Rivera and P. A. Hoss, J. of Appl. Phys., Vol. 37#13, 4743 (Dec 1966).

- The disagreement between experimental measurement of the reflectivity minimum of low-mobility semiconductors and simple theory is accounted for by inclusion of the imaginary part of the dielectric constant in deriving the carrier-concentration/-plasma-wavelength relationship. Data on the plasma wavelength of p-type gallium arsenide are presented.

NAVA71 "Carrier Relaxation Time from Infrared Reflection Spectra in Semiconductors." IR-IMP

(HgTe, CdO) G. Navascues and F. Flores, Solid State Communications, Pergamon Press, Vol. 9, pp. 1267-1270 (1971).

- When the carrier relaxation time in a semiconductor is estimated independently from reflectivity curves ($\tau_O$) and from Hall mobility data ($\tau_H$) it is frequently found that $\tau_O$ and $\tau_H$ disagree rather markedly. An explanation is often suggested in terms of statistical effects. Since this requires a sufficiently non-degenerate distribution and a strongly dispersive scattering mechanism, we explore another alternative invoking the role of a space charge boundary layer. Two examples are considered and the analysis yields quite reasonable results.

PHIL73 "Plasma Resonance on p-Type Gallium Arsenide." IR-IMP

(GaAs) John W. Philbrick, C. A. Pillus and C. P. Schneider, Solid State Tech., Vol. 16, 66 (April 1973).

- The variation of the position of the infrared reflectivity minimum with carrier concentration was determined from Hall effect and reflectivity measurements, unpublished data of other workers and selected data in the literature. The calibration curve for the determination of concentration from the position of this minimum is given. Concentrations determined from this equation agree with those determined from Hall measurements to $\pm$12.64% (1 std. dev.).

RAWL64 "Measurement of the Resistivity of Epitaxial Vapor Grown Films of Silicon by an Infrared Technique." IR-RHO

(Si,Ge) T. G. R. Rawlins, J. Electrochem. Soc., Vol. 111#7, 810 (July 1964).

- An infrared reflectivity technique is outlined whereby the reflectivity may be correlated with d-c resistivity of thin vapor deposited epitaxial silicon layers. The theory underlying the method is outlined and calculated curves for different planes of polarization are given. Experimental results are described for a range of resistivities between 0.03-60 ohm-cm. Limitations of the equipment used are discussed and the validity of the method examined.

THUR71 "Determination of Deep Impurities in Silicon and Germanium by Infrared Photoconductivity." IR-IMP

(Si) W. R. Thurber (National Bureau of Standards), NBS-TN-57D; March 1971, pp. 16, Microfiche N71-20614 (1 card).

- A literature search of a PC determination of deep impurity concentrations, noting difficulty with PC when more than one kind of deep trap is present.

TRON73 "Optical Absorption Edge and Raman Scattering in $Ge_X Se_{1-X}$." IR-IMP

(Se:Ge) P. Tronc, M. Bensonssan, A. Brenac and C. Sebenne. Phys. Rev. B8, 5947 (1973).

- Photon absorption and inelastic scattering.

BLAC72 "Nondestructive Photovoltaic Technique for the Measurement of Resistivity Gradients in Circular Semiconductor Wafers." OP-RHO

D. L. Blackburn and H. A. Schafft; J. Electro. Chem. Soc. Vol. 119#12, 1773 (1972).

- A practical alternative to the four-probe technique for making resistivity gradient measurements along the diameter of a circular semiconductor wafer is described in this paper. This technique, which is based upon the bulk photovoltaic effect of Tauc (5), requires no contact with the flat surface of the wafer and permits a continuous measurement of the resistivity gradient along the wafer diameter to be made.

BUGR70 "Measurement of the Resistivity Inhomogeneity of Photosensitive Semiconducting Materials by the Dark Probe Method." OP-RHO

V. I. Bugrienko and V. N. Rybin; translated from Fizika i Tekhnika Poluprovodnikov, pp. 1593-1597, October 1969. Soviet Physics-Semiconductors, Vol. 3#10, 1340 (April 1970).

- The "dark probe" method, proposed in the present paper for measuring the resistivity inhomogeneity of photosensitive semiconducting materials differs basically from the presently available methods. In order to reduce the total resistance the whole sample of length L is illuminated uniformly, with the exception of a narrow strip whose width is X.

CARR67 "Determination of Electrical Conductivity of Photoconductors Without Contacting Electrodes." OP-RHO RF-RHO

(Se,CdS, S) A. Carrelli, F. Fittipaldi and L. Pauciulo, J. Phys. Chem. Solids, Pergamon Press, Vol. 28, pp. 297-299 (1967).

- It is shown that it can be possible to determine electrical conductivity $\sigma$ of photoconductors and semiconductors without contacting electrodes from measurement of torque exerted on a suspended specimen, by a rotating electric field, E(t). The experiments were carried out with CdS, S, Se. Those measurements are in good agreement with the literature.

KARP62 "Recombination Properties of Gold in n-Germanium." OP-RHO

(Ge) I. V. Karpova, V. G. Alekseeva and S. G. Kalashnikov; translated from Fizika Tverdogo Tela, pp. 634-641, March 1962. Soviet Physics-Solid State, Vol. 4#3, 461 (September 1962).

- We have investigated the photomagnetic effect (PME) and photoconductivity (PC) in n-germanium doped with gold as functions of temperature and gold atom concentration.

KOKO62 "Analysis of the Homogeneity of Semiconductor Materials by Using the Method of the Volume Photo-emf." OP-RHO

D. T. Kokorev and N. F. Kovtonyuk; translated from Pribory i Tekhnika Eksperimenta, No. 2, pp. 160-164, March-April 1962. Instruments and Experimental Techniques, Vol. 5, 382 (1962).

- The present article explores the applicability of the method of the volume photo-emf for inspecting the homogeneity of semiconductor materials. It is shown that the emf in homogeneous semiconductors arises only due to the space charge, while, in inhomogeneous semiconductors, the emf connected with the nonuniformity of resistivity is added to the emf which is due to the space charge. Recommendations concerning the methods and schemes for plotting the inhomogeneity distribution curves are given. This method can be successfully used for inspecting thin semiconductor plates, for instance, plates of GELS-30/1.5 germanium.

OROS60 "Quantitative Photovoltaic Evaluation of the Resistivity Homogeneity of Germanium Single Crystals." OP-RHO

(Ge) J. Oroshnik and A. Many. Solid-State Electronics, Pergamon Press, Vol. 1, pp 46-53 (1960).

- An apparatus based on the bulk photovoltaic effect, is described by means of which quantitative estimates of the resistivity changes throughout germanium single-crystal samples may be realized. For material that is homogeneous in lifetime, the error may be as little as 3 per cent.

SPEA68 "Optical Probing of Inhomogeneities in n-GaAs with Applications to the Acoustoelectric Instabilities." OP-RHO

(GaAs) David L. Spears and Ralph Bray; Journal of Applied Physics, Vol. 39#11, 5093 (October 1968).

- A study is presented of the intimate relationship between current instabilities of acoustoelectric origin in n-GaAs at 77°K and the inhomogeneity in the Ohmic resistivity of the samples. In order to correlate various aspects of the acoustoelectric instabilities with the sample inhomogeneities, two optical probing techniques were developed for determining the Ohmic-resistivity profile with good spatial resolution, ≳0.1mm. One involves the measurement of the local photoconductance in the sample, which is related to the local dark resistivity; the other method involves the measurement of the change in optical transmission produced by the local thermal shift in the intrinsic absorption edge when the sample is heated by a high current pulse. The change in optical transmission is related to the local resistivity. The acoustic flux distribution in the sample is determined by yet another optical probe, utilizing the modulation in transmission produced by the high acoustic-energy density in the domain. Several aspects of the acoustoelectric effects are themselves useful for gauging the homogeneity of the samples. In particular, the propagating acoustoelectric domain serves as a convenient probe of the carrier concentration. These techniques are applied to the analysis of the form of the current instabilities, the distribution of the acoustic flux in the sample, and the domain-formation process. The presence of a somewhat higher resistance, hence higher acoustoelectric-gain region, at the upstream end near the cathode is shown to contribute to the formation of propagating acoustoelectric domains.

SUBA63 "Determination of Semiconductor Parameters from the Photomagnetic Effect and Photoconductivity." OP-RHO

V. K. Subashiev, translated from Fizika Tverdogo Tela, pp. 556-558, February 1963. Soviet Physics-Solid State, Vol. 5#2, 405 (August 1963).

- The basis is given for an improved variant of the method for determining the parameters of a uniform semiconductor from the photoconductivity and photomagnetic effect response spectra.

THOM55 "High-Sensitivity Photoconductor Layers." OP-RHO

(CdS) S. Milton Thomsen and Richard H. Bube. The Review of Scientific Instruments, Vol. 26#7, (July 1955)

- High-sensitivity photoconductor "powder" layers and "sintered" layers have been prepared in large-area form, with most of the desirable characterisitics of single crystals. At an illumination of 1 ft-c, ratios of photocurrent to dark current as large as $10^6$ may be obtained for both types of layers.

CHEN72 "Photothermoelectric Analysis of Chemically Deposited Cadmium Sulfide Layers." OP-MU

(CdS) Chen-ho Wu, Robert S. Feigelson and Richard H. Bube, J. Appl. Phys., Vol. 43#2, 756 (February 1972).

- Carrier mobilities in the few thousandths $cm^2/V$ sec can be reliably inferred from thermoelectric power measurements, considerably smaller than can be determined by standard Hall measurements. Techniques of photothermoelectric analysis are applied to chemically deposited layers of CdS and CdS-CdSe, as prepared, and after photosensitization by impurity diffusion. Photoconductivity in the unsensitized films is due wholly to an increase in mobility in the sensitized films, both carrier density and mobility increase with photoexcitation. The high-light mobility is increased by a factor of $10^2$ by impurity sensitization.

EISE72 "Double Modulation Method for Hall Effect Measurements on Photoconducting Materials." OP-MU

I. Eisele and L. Kevan, The Review of Scientific Instruments, Vol. 43#2, 189 (Feb 1972).

- A new double modulation method for photo-Hall mobility measurements on high impedance photoconductors is described. The magnetic field is modulated by rotating the sample in the field and the density of charge carriers is modulated by chopping the light beam which induces photoconductivity. The Hall signal is detected at the sum frequency of the two modulations and a clear distinction in phase and frequency between the Hall signal and different error signals is obtained.

ROBE68 "Investigation of the Homogeneity of CdS Crystals Using an Optical Probe." OP-MU

(CdS) G. I. ROBERTSON and E. A. Ash; Solid-State Electronics, Pergamon Press, Vol. II, pp. 603-612 (1968).

- The internal inhomogeneities in resistivity, electro-mechanical coupling constant and electron drift mobility in photoconducting CdS Acoustic Amplifier crystals are measured using an Optical Probe. The Probe consists of a laminar, amplitude-modulated beam of light projected through the crystal and superimposed on the normal illumination. The inhomogeneity information is carried as an a.c. component of the current or ultrasonic signal through the crystal. Results indicate marked inhomogeneities in all these parameters, and point strongly to the fact that the electron drift mobility variation is a primary cause of the resistivity variation in the sample.

SMIT69 "Photo-Hall Measurement by an Improved Redfield Method." OP-MU

G. C. Smith. The Review of Scientific Instruments, Vol. 40#11 1454 (November 1969).

- Improvements in electrodes and in instrumentation allow measurement of Hall mobilities as low as 1 $cm^2/V \cdot sec$ in photoconducting insulators.

VORO71 "Determination of the Mobility in Small Samples of Gallium Arsenide from Magnetoresistive Effects." OP-MU

V. N. Vorob'ev and Yu. F. Sokolov, Soviet Physics - Semiconductors, Vol 5#4, 616 (October 1971).

- A method was developed for the determination of the mobility in n-type GaAs under laser oscillation conditions. The method is based on the dependence of the laser threshold current on the magnetic field. An analysis is made of the physical meaning of the mobilities $\mu_i$ and $\mu_m$ found by the threshold-current and the magnetoresistance methods, and of the relationship between these mobilities and the Hall value $\mu_h$. It is shown that, if the true mobility is taken as $\mu=\mu_i \approx \mu_m$, it becomes possible to explain much of the experimental data on the dependence of the threshold current and voltage on the transverse magnetic field.

WALT70 "Conduction Band Effective Mass in N-Type Silicon." OP-MU

(Si) A. K. Walton and P. L. Reimann, Department of Physics, University of Sheffield, p. 1410 (1969).

- Measurements of the infrared free carrier dispersion and Faraday rotation in N-type silicon are reported. Combination of the dispersion and Faraday rotation results gives an entirely optically determined room-temperature transverse effective mass of $(0{\cdot}225 \pm 0{\cdot}01)m$ yields the carrier concentrations in the specimens. Previous effective mass determinations involving Hall effect experiments must be suspect.

BAEV66 "An Investigation of the Distribution of Inhomogeneous Regions in Semiconductors." OP-TAU OP-RHO

(Ge) I. A. Baev and E. G. Valyashko; translated from Fizika Tverdogo Tela, pp. 2585-2593, September 1965. Soviet Physics-Solid State, Vol. 7#9, 2093 (March 1966).

- The results of a study of inhomogeneities of $\rho$ and $\tau$ in semiconductor crystals are presented. The theory of the bulk photovoltaic effect was used to derive expressions useful in the quantitative evaluation of grad $\rho$ in the various inhomogeneous portions of the crystal using experimentally determined values of the bulk photo-emf and of the photoconductivity of the material.

GERS70 "Effect of the Spatial Carrier Distribution on the Cyclotron Resonance Spectrum." OP-TAU

(Ge) E. Gershenzon, E. Gusinskii, R. Rabinovich and N. Soina, Sov. Phys. Sol. St. 12#6, 1389 (1970).

- Photoexcited carriers in pure Ge show strong dependence of their cyclotron resonance spectra on their spatial distribution.

HARP70 "Photothermoelectric Effects in Semiconductors: η- and ρ-Type Silicon." OP-TAU

(Si) James G. Harper, Herman E. Matthews and Richard H. Bube, Journal of Applied Physics, Vol. 41#2, 765 (February 1970).

- The ability of thermoelectric power measurements to permit a description of carrier-density and phonon-drag variations caused byphotoexcitation was tested in 100 Ω•cm η- and ρ-type silicon. At low temperatures the major effect of photoexcitation is to decrease the phonon-drag contribution to the thermoelectric power by increasing the phonon density in the crystal. At higher temperatures the thermoelectric effect can be used to investigate changes in the electronic contribution due to photoexcitation. An apparently anomalous increase in thermoelectric power with photoexcitation was consistently found in ρ-type silicon over an intermediate temperature range.

HAYN74 "The COMSAT Non-Reflective Silicon Solar Cell: A Second Generation Improved Cell." OP-TAU

(Si) J. Haymos, J. Allison, R. Arndt and A. Muellenberg, International Conference on Photovoltaic Power Generation, Hamburg, Germany, September 25-27, 1974, reprints available from COMSAT Laboratories, Box 115, Clarksburg, Md., 20734.
- Photovoltage vs. wavelength show improvement with controlled surface roughness of Si.

HENI56 "Contactless Method for the Estimation of Resistivity and Lifetime of Semiconductors." OP-TAU RF-RHO

H. K. Henisch and J. Zucker, Rev. Sci. Inst., Vol. 27 (1956).

- In the processing of semiconducting materials, it is often desirable to estimate the resistivity and bulk lifetime of charge carriers rapidly and without special shaping of the specimens. The device described in this note is designed to accomplish this. Lifetime is measured by illuminating the specimen while it is near the coil and determining the losses introduced by the resulting photoconductivity.

IGLI71 "Photoelectric Determination of the Homogeneity of Specific Resistance and Excess-Carrier Lifetime in Silicon." OP-TAU OP-RHO

M. I. Iglitsyn, E. P. Berdnikov, V. V. Voronkov and G. I. Voronkova; Industrial Lab Vol. 37, 878 (Jan-June 1971).

- Semiconductor devices with large active areas (power devices, radiation detectors, etc.,) have to be manufactured from silicon crystals of homogeneous specific resistance $\rho$ and excess-carrier lifetime $\tau$ [1-4]. The present methods of measuring the homogeneity of these parameters are quite laborious and not always sensitive enough. Here we describe a simple method of simultaneous and continuous determination of $\rho$ and $\tau$ as well as of their inhomogeneity in high-resistance silicon crystals which is based on measuring photoconductivity at two modulation frequencies.

KVST70 "Spectral Photosensitivity of Inhomogeneous Semiconductors." OP-TAU

(GaAs) V. G. Kustov, V. P. Orlov, V. A. Presnov and B. S. Azikov, Soviet Physics - Semiconductors, Vol 4#4, 567 (October 1970).

- An analysis is made of the influence of local inhomogeneities on the photoconductivity spectrum and on the spectrum of photoconductivity quenching. GaAs is used to demonstrate that an inhomogeneous distribution of recombination parameters across a sample alters the nature of the photoconductivity spectrum beyond the fundamental absorption edge.

LIND73 "The Violet Cell: An Improved Silicon Solar Cell." OP-TAU

(Si) J. Lindmayer and J. F. Allison. ComSat Technical Rev. 3#1 1-22 (Spring 1973).
- Photovoltage measurements vs. wavelength reveal the controlling importance of carrier recombriation in the improved "violet" solar cell devices on the scale of 1000Å.

MAKH69 "Method of Measuring the Faraday Effect in Semiconductors." OP-TAU

(Ge) Yu. A. Makhalov; Instrum. and Exp. Tech. Vol. 12#2, 1593 (July-Dec 1969).

- The Faraday effect is used for measuring the effective mass of the current carriers in semiconductors and for studying interband transitions. A method is suggested for measuring the angle of rotation of the plane of polarization up to $\pm 0.2^{o}$, based on the use of light with variable polarization.

NAM76 "Free-Exciton Energy Spectrum in GaAs." OP-TAU

(GaAs) S. B. Nam, D. C. Reynolds, C. W. Litton, R. J. Almassy and T. C. Collins, Phys. Rev. B13 (Scheduled 15 Jan 1976).

- Photoluminescence and reflection at 6471Å are used to observe the excited states of the free exciton in GaAs, as well as the ground state, up to 40 kG magnetic field.

SCHE75 "Photovoltaic Properties of Anisotropic Relaxation Semiconductors." OP-TAU

J. F. Schetzina, Phys. Rev. B12#10 (1975).

- The anomalous photovoltaic effects frequently observed in GaAs and other anisotropic semiconductors are explained in terms of a theory for the influence of nonuniformities on the carrier relaxation.

SEKI71 "Photocurrent and Carrier Distributions Due to Steady Light Absorbed in Finite Thickness." OP-TAU

H. Seki and B. H. Schechtman; J. Appl. Phys., Vol. 43#2, 523 (February 1972).

- The steady-state photocurrent through a layer of photoconducting material is investigated when one of the surfaces is illuminated by a constant light source. The material is assumed to be intrinsic and free of deep traps, light penetration is characterized by an optical absorption coefficient, and bulk recombination is taken into account.

ULBR73 "Energy Relaxation of Photoexcited Hot Electrons in GaAs." OP-TAU

(GaAs) R. Ulbrich, Phys. Rev. B8, 5719 (1973).

- Photoinduced conductivity permits observation of $\tau$ vs. carrier energy in high mobility semiconductors.

VDOV73 "Lifetime of Nonequilibrium Carriers in Single Crystals of $Cd_xHg_{1-x}Te$." OP-TAU

(HgCdTe) E. E. Vdovkina, N. S. Baryshev, F. P. Volkova, A. P. Cherkasov, M. P. Shchetinin and I. S. Aver'yanov. Inorganic Materials, Vol. 9#1, 115 (1973).

- The lifetime was determined by means of measurements of the photoelectromagnetic effect (PME) and the photoconductivity (PC) of n-type specimens with uncompensated donor concentrations of about $10^{15}$ $cm^{-3}$ in the range from 77 to 300°K. For the photoelectric measurements we selected the most homogeneous specimens in which there were no parasitic photo-emfs associated with composition or carrier-concentration gradients. The lifetimes found from the separate measurements of the PC and PME and those determined by the method of PC/PME ratios were practically equal, since there is no appreciable capture of nonequilibrium current carriers in the range of temperatures used.

BAEV64 "Study of the Homogeneity of Semiconductor Crystals with the Use of a Moving Light Probe." OP-IMP

(Ge) I. A. Baev and E. G. Valyashko; translated from Fizika Tverdogo Tela, pp. 1729-1734, June 1964. Soviet Physics-Solid State, Vol. 6#6, 1357 (December 1964).

- A method is proposed for studying semiconductor crystals by way of the bulk photo-emf which arises when a light probe is moved across inhomogeneous portions. If the inhomogeneity is related to a nonuniform distribution of impurities, the relative magnitude and direction of the concentration gradient can be determined.

BEBB72 "Photoluminescence I: Theory." OP-IMP

(GaAs) H. Barry Bebb and E. W. Williams; Semiconductors and Semi-Metals Edited by R. K. Willardson and Albert C. Beer, Transport and Optical Phenomena, Academic Press, NYC, Vol. 8, pp. 181-321 (1972).

-A major purpose of the present article is to provide an introduction to the theoretical and experimental aspects of the photoluminescence at the research level. In order to maintain self-consistency throughout the article, our development of a subject will often differ in notation and form from the original literature. On the experimental side our purpose is to bring together all of the important independent empirical results and take an overview of the collection of findings to establish what is actually known and what needs additional experimental or theoretical work.

FABR71 "Scanning Photoluminescence on Gallium-Arsenide." OP-IMP

E. Fabre, Solid State Communications, Pergamon Press, Vol. 9, 635 (1971).

- Photoluminescence measurements on high purity η-type epitaxial Gallium-Arsenide have shown a correlation between relative intensities of two recombination peaks at 1.515eV and 1.489eV and the compensation ratio deduced from Hall effect measurements. It is possible to study the homogeneity of compensation by scanning the laser excitation.

HENR73 "Simplified Analysis of Electron-Hole Recombriation in Zu- and O-doped GaP." OP-IMP

(GaP) C. H. Henry, R. Z. Bachrach and N. E. Schumaker, Phys. Rev. B8 4761 (1973).
- Photoluminescence from impuritysites - theoretical.

HERM68 "Spectral Analysis of Photoemissive Yields in GaAs and Related Crystals." OP-IMP

(GaAs) Frank Herman and William E. Spicer, Physical Review, Vol. 174#3, pp. 906 (15 Oct 1968).

- An improved energy-band model for GaAs is reported.

KRES68 "Luminescence in Silicon-Doped GaAs Grown by Liquid-Phase Epitaxy." OP-IMP

(GaAs:Si) H. Kressel, J. U. Dunse, H. Nelson and F. Z. Hawrylo, Journal of Applied Physics, Vol. 39#4, 2006 (March 1968).

- The radiative processes in closely compensated GaAs doped with Si (ρ-type) and Si+Te (η-type) have been studied by photoluminescence between 300°and 77°K. These materials were grown by liquid-phase epitaxy. The results strongly suggest that Si introduces two acceptor levels in GaAs with ionization energies of approximately 30 meV and ∿100 meV.

KRES68B "Observations Concerning Radiative Efficiency and Deep-Level Luminescence in η-Type GaAs Prepared by Liquid Phase Epitaxy." OP-IMP

(GaAs:Te) H. Kressel, F. Z. Hawrylo, M. S. Abrahams and C. J. Buiocchi, Journal of Applied Physics, Vol 39#11, 5139 (October 1968).

- A study was made of η-type GaAs prepared by liquid-phase epitaxy doped with Si, Ge, Sn, Te and Se by photoluminescence and Te-doped material by transmission-electron microscopy. A broad emission band centered at 1.2 eV (band B) is observed in LPE materials doped with group VI elements.

KURB70 "Cathodoluminescence of Gallium Arsenide." OP-IMP

(GaAs) L. N. Kurbatov, N. N. Mochalkin and A. D. Britov. Translated from Fizika i Tekhnika Poluprovodnikov, Vol. 4, No. 1, pp. 62-66, January 1970. Original article submitted April 2, 1969.

- An investigation was made of the influence of the impurity concentration, the density of the incident fast electrons, and the temperature on the spontaneous and coherent luminescence of gallium arsenide. The data obtained indicate that the spontaneous luminescence spectrum has several maxima associated with different transitions: band-band, band-impurity, and impurity-impurity. The intensities of these transitions depend in different ways on the impurity concentration, the degree of compensation of the sample, the excitation level and the temperature.

LEHE75 "Optical Pumping in Nitrogen-Doped GaP." OP-IMP

(GaP) R. F. Leheny and J. Shah, Phys. Rev. B12#10 (1975).

- Photon absorption resonant with the deep traps formed by N in GaP is used to study impurity density and the charged traps so formed.

LEMK75 "Origin of EPR Signal from Silicon Surfaces." OP-DEF

B. Lemke and D. Haneman, Bull APS 20#12, 1502 (1975).

- EPR signals are traced to microcreecles on silicon surfaces cleaved in UHV at low temperatures at g=2.0055; the lowest spin density corresponded to $3+2\times10^{12}cm^{-2}$.

OMEL69 "Equipment for Studying Galvanomagnetic Thermal and Photo Effects in High-Resistance Semiconductors (Exchange of Experience)." OP-IMP

E. M. Omel'yanovskii and N. N. Sobov'ev. Industrial Lab., Vol. 35#2, 1215 (July-December 1969).

- Apparatus has been constructed for measuring resistivity and Hall effect which is also used to study thermal and photoeffects and photoconductance on various semiconductor materials with resistivities up to $10^{-10}$ Ω•cm.

ORL071 "Use of the Faraday Effect for Investigating the Distribution of Current Carrier Concentrations in n-Type GaAs." OP-IMP

(GaAs) P. B. Orlov, L. I. Kolesnik and Yu. V. Kudin, translated from Zavodskaya Laboratoriya, pp. 440-444, April 1971; Industrial Lab., Vol. 37, 562 (Jan-June 1971).

- The contactless methods which are now more and more extensively used for investigating semiconductor characteristics also include methods by which the concentration of current carriers is measured. Determination of the local concentration would make it possible to examine the distribution of impurities in semiconductor materials. The authors have developed a contactless method of measuring the current carrier concentration in n-type GaAs single crystals by means of the magneto-optic Faraday effect.

ROSS70 "Acceptor Luminescence in High Purity η-Type GaAs." OP-IMP

(GaAs) J. A. Rossi, C. M. Wolfe and J. O. Dinnock, Physical Review Letters, Vol. 25#23 1614 (Dec 1970).

- Photoluminescence of epitaxial GaAs in a magnetic field has established the origin of several recombination transitions 20 to 40 meV off the band edge.

SHAH69 "Photoluminescence and Photoconductivity in Undoped Epitaxial GaAs." OP-IMP

(GaAs) Jagdeep Shah, R. C. C. Leite and R. E. Nahory, Physical Review, Vol. 184#3, 811 (15 August 1969).

- We have measured the photoluminescence and the photoconductivity spectra of pure epitaxial GaAs. The photoluminescence spectra at $2^{o}$K show 11 sharp peaks (widths 0.1-1.0 meV) between 1.509 and 1.516 eV. The photoconductivity spectra show relatively sharp peaks (widths ≳2meV) which correspond in energy to some of the emission lines.

SUMM70 "Far-Infrared Donor Absorption and Photoconductivity in Epitaxial n-Type GaAs." OP-IMP

C. J. Summers and R. Dingle, Physical Review B, Vol. 1#4, 1603 (15 Feb 1970).

- Donor-state absorption and photoconductivity spectra of n-type epitaxial GaAs layers with carrier concentrations in the range $10^{14}$-$10^{16}/cm^3$ are reported. The essentially effective mass-like behavior of the impurity spectra is confirmed, and ionization energies of 6.08, 5.81, 5.89 and 5.10±0.025 meV are reported for Ge, Si, Se and S donors. The influence of impurity-banding upon the values of $E_D$ is considered. Central-cell corrections to donor ground-state energies are discussed.

WILL67 "The Observation of Defects in GaAs Using Photoluminescence at 20°K." OP-IMP

E. W. Williams and D. M. Blacknall, Transactions of the Metallurgical Society of AIME, Vol. 239, 387 (March 1967).

- Low temperature measurements of photoluminescence were used to evaluate the progress in materials development. Variation of the impurity type, impurity concentration and method of growth were used to clarify the chemical origin of defects in GaAs.

WILL69 "Luminescence Studies of a New Line Associated With Germanium in GaAs." OP-IMP

E. W. Williams and C. T. Elliott, Brit. J. Appl. Phys (J. Phys. D.), Ser. 2, Vol. 2, 1657 (1969).

- A luminescence line has been observed at 1·454 ev at 20°K in germanium-doped GaAs. Measurements have been made of the peak energy, intensity and half-width as a function of temperature.

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(GaAs) E. W. Williams and C. T. Elliott; Brit. J. Appl. Phys. (J. Phys. D), Ser. 2, Vol. 2, 1657 (1969).

- A luminescence line has been observed at 1·454 ev at 20°K in germanium-doped GaAs. Measurements have been made of the peak energy, intensity and half-width as a function of temperature. It is proposed that the centre responsible for the luminescence is an arsenic vacancy bound to a germanium atom on an arsenic site. Preliminary results indicate that a similar centre is present in silicon-doped GaAs grown from a gallium solution.